SYSTEMS ENGINEERING, MANNED SPACE FLIGHT

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Introduction

The systems engineering activities of the United States in manned space flight have involved the design, development, manufacture, test, and operation of three flight systems--Mercury, Gemini, and Apollo. The overall arrangement of these configurations is illustrated in Figure 1. The systems engineering effort has not only encompassed these space vehicles, but also encompasses many other aspects of the programs such as worldwide instrumentation and communications networks, control centers, recovery support and equipment for the conduct of various scientific and technical experiments. As experience has evolved from development efforts and flight operations, certain factors have become apparent related to the achievement of well balanced and functional systems. Some of these factors will be discussed herein.

Program Objectives

The point of departure for systems engineering work involves the definition of objectives for any given space flight program. In the programs just mentioned, primary objectives have been stated in fairly simple and direct terms, as indicated in Figure 2. The Mercury Program was aimed at the demonstration of manned orbital flight and safe return. The Apollo Program is aimed at manned lunar landing and safe return. The Gemini Program involved a somewhat broader range of objectives, but in the conceptual design, long duration flight and rendezvous received the main emphasis. All of these programs carry with them a substantial number of secondary objectives; however, the primary objectives tend to dominate the design and it is quite important not to confuse early efforts with a large multiplicity of objectives. At the same time, sufficient consideration of secondary objectives must be applied in order to avoid basic constraints that might make their achievement impossible. In Gemini, for example, such considerations involved the hatch design to afford extravehicular possibilities, the docking adapter design to afford maneuvering in orbit with a large propulsive stage, and design control of center of gravity offset to afford the possibilities of maneuvering reentry.

Mission Modes

Once the objectives of the flight program have been clearly established, it is necessary to analyze various mission modes by which these objectives can be achieved. This mission mode analysis ultimately establishes the design missions and environmental conditions upon which the configuration of the flight hardware is based. The broadest and most basic example of this systems engineering task is associated with the Apollo objective and is the work which led to the decision to use the lunar orbit rendezvous mode.

This mode selection question involved many of the classical elements of a complicated systems engineering problem. It involved money, time, the state of current technology, the status of space hardware development in the United States, the fallback positions available in case of technical problems, the probability of mission success and, last but not least, the question of astronaut safety. Each of three mission modes were evaluated with respect to these kinds of factors and the final selection made with the best possible intercomparison among all of them.

The three modes which were seriously considered (together with variations) are illustrated in Figure 3 and briefly described in the following paragraphs.

Direct Launch Mode - The basic profile of this mode starts with a simple launch from the earth directly into earth-moon transfer much like several of the Surveyor missions. No earth orbit phase is included. At the moon, the descent is directly to the lunar surface without first establishing a circular lunar orbit, much like Surveyor.

Two hardware configurations were considered for the direct mode. One consisted of a launch vehicle of the Saturn V class with a somewhat cramped two-man spacecraft. The other plan utilized a larger (NOVA) design together with a three-man spacecraft of more comfortable design.

Earth Orbit Rendezvous - The earth orbit rendezvous mode involves two or more earth launches (two was considered in the Apollo study) and assembly of a spacecraft/injection stage in orbit. This mode provided the potential for using a three-man spacecraft without going to a booster of the NOVA class (about 75 tons to escape velocity). The lunar phase of the mission for the case considered was the same as for the direct ascent mode with a three-man spacecraft. Obviously, there are possibilities for combining earth rendezvous and lunar orbit rendezvous modes. These were not considered since they offered no advantage in the Apollo mode trade-off study.

Lunar Orbit Rendezvous Mode - For the direct ascent and earth orbit rendezvous modes already discussed, a relatively heavy spacecraft had to be landed on the moon and subsequently launched back toward earth. All of the fuel for the trans-earth journey and the heat shield for reentry into the earth's atmosphere are part of the payload landed on the moon. With the lunar orbit rendezvous mode, both of these items, in addition to structure and engines, remain in lunar parking orbit. This avoids both the need to slow down all of the weight for landing and then accelerate it during launch and transearth injection maneuvers. The spacecraft for the lunar orbit rendezvous mode is thus composed of a different combination of stages than would be appropriate for direct ascent to the surface. Since it is lighter for the same payload to the moon, the earth launch payload requirements are lower.

The various modes studied required different hardware developments, and design studies were accomplished to clarify both hardware and mission configurations. From these studies, estimates were developed for costs, time, success probabilities and safety. Some of these rather elusive factors were easier to compare than to estimate on an absolute basis. The results of some of the studies are shown in Figure 4. It can be seen that the lunar orbit rendezvous mode was equal or best in all characteristics listed. This is consistent with the choice being unanimous among NASA management at the time it was made.

Operational Features of Lunar Orbit Rendezvous - Another important feature of a mission is the crew activities timeline. In this respect, too, the lunar orbit rendezvous mode has some attractive features. It is generally desirable to have the mission arranged so that transition periods of relatively high activity and stress are relieved by periods of relative stability and freedom from imminent pressures. In mission planning language, these periods are sometimes called steps and "plateaus," respectively. The lunar orbit rendezvous mode provides the maximum number of plateaus among the various modes considered.

To leave one plateau and transfer to another normally involves a powered flight maneuver. After this event, there is an opportunity (on the plateau) to assess the status of the spacecraft itself, assess the maneuver just completed, and to review the available options for the next event or step. The options usually include the nominal next step, perhaps corrected for the dispersions encountered previously, plus one or more alternates. One of the various alternates is chosen only if there is a reason to discontinue the nominal mission. The differences between alternates can be categorized by the relative accomplishment in terms of completing mission objectives or gaining flight experience, in terms of the time or propulsion required, or in terms of the lessening of burdens on various subsystems. An alternate mission of unusual urgency is commonly called an abort.

The existence of convenient plateaus, coupled with the planning of mission alternatives which can be selected in real time, provides considerable flexibility in conduct of the mission. Before launch the mission plan is the nominal one including accomplishment of all objectives. As time goes on, modifications can be made as necessary to accommodate real time events while achieving as much applicable flight experience as possible. For a mission as long as the lunar mission, this approach is expected to provide real advantages. It allows making as much progress as conditions will permit, i.e., capitalizing on success while being able to respond to adversity. This approach is part of an "all-up" concept which may be contrasted to the more common approach of arranging a long series of successive missions, each slightly more complicated than the previous one.

The plateaus which naturally occur in the lunar orbit rendezvous mission are listed in Figure 5. The end points of these plateaus representing major "commit" points in the lunar landing mission are characterized by propulsive maneuvers resulting in major changes in the spacecraft energy. These commit points and mission plateaus can both be represented schematically on a single chart as shown in Figure 6. This figure illustrates the major maneuvers during the lunar landing mission in terms of both delta V (on the left) and pounds of propellant (on the right). These maneuvers represent the "commit" points, and the space in between represents the plateaus.

A similar approach was taken in establishing the mission mode for the initial Gemini rendezvous, although later in the flight program many different techniques were explored. Three different rendezvous techniques were analyzed. These techniques are illustrated in Figure 7. Rendezvous planning began over three years before the first rendezvous mission was performed. This planning began with the selection of the basic mission design criteria which would be used for all of the eventual studies that were performed and conducted.

The basic criteria were really very simple. Consideration was given almost exclusively to providing the highest probability of mission success. That is, the intention was to design a mission which could routinely depart from the nominal in response to trajectory dispersions and/or spacecraft systems degradation, while still providing minimum dispersion of the conditions going into the terminal phase. More specifically, it was to provide flexibility without introducing undue complexity, thus giving the astronauts and flight controllers a capability of choosing alternate maneuver sequences not dissimilar to the basic maneuver sequence, but which would provide a capability of reacting to the aforementioned dispersions and problems.

Returning to Figure 7, the three plans that were prepared and documented were:

Plan 1 - The so-called tangential mission plan, which provided rendezvous after approximately three and a half orbits;

Plan 2 - The coelliptic, which utilized the same basic midcourse phase maneuver sequence but which had a significantly different terminal phase; and

Plan 3 - A rendezvous at first apogee.

Based on analysis of these plans, a recommendation was made to adopt the second. The basic desired feature of the coelliptic plan was that the relative terminal phase trajectory of the spacecraft with respect to the target was not particularly affected by reasonable dispersions in the midcourse phase maneuvers. More simply stated, the coelliptic approach afforded a "standardized" terminal phase trajectory which yielded obvious benefits with regard to establishment of flight crew procedures and training.

Systems Selection and Configuration

Once the selections of mission modes and design missions have been made, a further clarification of the approach to the hardware design is possible. This approach involves consideration of the state-of-the-art of potential systems, the developmental status of systems that could be applicable, and the requirements for new systems development. In the selection of the systems and types of operations to be demonstrated, a strong effort is made to consider the requirements of future programs. It is not anticipated that such systems necessarily will be directly used in other programs; however, their operating principles should be sufficiently close that the concepts for their use can be validated. Where possible and to minimize development time, systems that already have some development status are selected. The Gemini spacecraft guidance system typically represents this approach. A simplified block diagram of this system is shown in Figure 8. The system is capable of carrying out navigation, guidance, and the precise space maneuvers needed for such activities as rendezvous, maneuvering, reentry, and launch guidance. At the same time, such major elements of the system as the inertial platform, the digital computer, the radar, and the flight-director display drew heavily on previous developments.

There are cases, however, where the state-of-the-art must be extended. A fact of extreme importance is the necessity to recognize the need for extending capabilities where the requirements of present or future programs lead to that conclusion. The Gemini fuel cell development is believed to be a good example of the exercise and recognition of such a requirement. These electric power generating devices, along with the long term cryogenic storage of hydrogen and oxygen, were an entirely new development not previously utilized even in ground applications. The Apollo system also uses fuel cells and can now draw on the Gemini experience. This development has also stimulated ground applications of similar devices.

Another factor requiring due consideration involves the choice of systems configurations achieving desirable operational characteristics. Some of the factors involved in this consideration are listed in Figure 9. Considerable operational difficulty was experienced with the Mercury spacecraft configuration which was very weight critical and could not afford many desirable operational characteristics. These difficulties resulted in launch delays, lengthy retest periods after modifications or component replacements, and a lower level of reliability than desired. As a result, heavy emphasis was placed upon achieving truly operational configurations for Gemini and Apollo. The Gemini vehicle, for example, was assembled from a number of discrete modules which generally accomplished a single particular function. Interfaces between the modules were as simple as possible. Each module was capable of being built and tested independently of the other modules. The parallel approach that this makes possible has greatly facilitated Gemini assembly, testing, and late replacement of malfunctioning modules.

In addition to the physical modularization, Gemini attempted to make each subsystem as independent as possible of other subsystems. This permits more thorough testing at a lower assembly level and avoids lengthy retests of many subsystems when a single component fails. In most cases, it was necessary to break electrical or plumbing connections to Mercury equipments for pre-flight testing and checkout. This required validation of the reconnection after test completion. During system design of the Gemini and Apollo, a determined effort was made to make all necessary test points, routine as well as diagnostic, available in the form of special test connectors. Difficulties with the "layered" Mercury equipment installation led designers to adopt the ground rule that each unit must be individually accessible and individually removable without disturbing other units. No unit could be installed in the pressure cabin unless it was specifically required by function to be there. The philosophy of individual accessibility was applied also to wire bundles and plumbing to avoid any need for threading these through structure or distorting them during installation. Mercury experience taught us that aircraft processes were not necessarily adequate for manned spacecraft. The manned space vehicle programs pioneered in a number of areas such as all brazed propulsion system plumbing, crimped electrical connections, salt free cold plate brazing, etc.

The modular concept was another factor involved in the selection of.the lunar orbit rendezvous mode for the Apollo system. This mode affords the use of a special purpose vehicle for carrying out the descent to and landing on the moon and the subsequent launch and re-rendezvous with the mother spacecraft. This special vehicle is called the lunar module and is shown in Figure 10. The efficacy of the approach taken can be envisioned when one considers the many operating regimes that must be traversed during the lunar mission. Provisions must be made in the system for traversing the launch environment, for aborting the launch, for long duration operations to and from the moon, for lunar landing, and for super-critical reentry on the return to earth.

A single vehicle or module encompassing all these capabilities would be severely compromised with respect to the lunar landing operation. For example, a very high landed weight would be required, flexibility of the system layout and visibility would be compromised because of reentry heat protection considerations, and the design of the propulsion, guidance and control systems for ascent and descent would be compromised by the maneuvering requirements associated with other parts of the mission. In the design of the lunar module, many of these compromises can be avoided and, therefore, this module becomes a truly special purpose spacecraft whose structure, external and internal configuration, and system operating characteristics reflect solely its unique function in the mission.

Redundancy and Crew Integration

Another important facet of systems engineering for manned space flight involves the use of redundant or backup systems. This technique must be applied judiciously and, as a result, in the spacecraft systems utilized to date a complete range of combinations exists. For systems directly affecting crew safety where failures are of a time-critical nature, on-line parallel redundancy is often employed. In the spacecraft pyrotechnics system, a complete parallel redundancy is often carried to the extent of running separate wire bundles on opposite sides of the spacecraft. In a few time-critical cases, off-line redundancy with automatic failure sensing is required. The flight control system of a launch vehicle is an example where this technique is frequently employed. In most crew-safety cases which are not time critical, crew-controlled off-line redundancy or backup is utilized with the crew exercising management of the systems configuration. In the spacecraft propulsion system, the reentry attitude control system is utilized solely for that phase of the mission. This reentry propulsion in turn involves parallel redundancy because of the critical nature of this mission phase. Many systems not required for essential mission phases are basically single systems with internal redundancy features commensurate with the requirements for overall mission success. Certain systems have sufficient inherent reliability once their operation has been demonstrated and no special redundant features are required. The spacecraft heat protection system is one of this type.

For systems which are very critical from the flight-safety standpoint, much attention is paid to obtaining flexibility in system operation and safety against successive failures of individual components. The Gemini electrical power and distribution system will be used here to illustrate a typical approach. A simplified schematic of this system is presented in Figure 11. The primary source of electrical power in orbit during long duration operations is the fuel cell. Two fuel cell sections are carried in the equipment adapter module to provide the basic system redundancy. Each section contains three stacks wired in parallel and each stack can be operated independently at the discretion of the crew. Normally, all stacks are placed on the line because low load operation has been shown by test to be extremely beneficial to fuel cell life. The crew, by monitoring the voltage output of each stack in relation to the load, can evaluate the load sharing of the stacks and determine whether all are operating within tolerance. In the event of a stack failure, and this did occur on a number of occasions, the crew may shut it down and, if necessary, exercise management over power consuming systems to reduce the overall load.

The fuel cell system is further backed up by a battery system contained within the reentry module. This battery system has the capacity to handle the power drains required for one and one-half orbits at full load, or much longer if the spacecraft is powered down. In addition to this capability, it provides required power for retro-fire and reentry, and that required for thirty-six hours of operation of necessary equipment after landing. The battery system itself has two sections--a main battery section which provides for general supply of power and a squib battery section which provides power for critical operations such as the firing of retro-rockets and pyrotechnics and the operation of flight controls. Again, it is possible for the crew, through manual switching, to provide main bus power to the critical squib circuits. Proper isolation is provided so that failure of one system does not jeopardize the other.

As shown by this example, manned spacecraft systems designs employ manual sequencing and systems management to a large extent. This feature affords simplicity by utilizing man's capability to diagnose failures and to take corrective action. It facilitates flexibility in the incorporation of necessary redundancy or backup configurations of the systems. For example, in the spacecraft electrical power system just illustrated, the redundancy involved would make automatic failure sensing, interlocking, and switching both complex and difficult, if not impossible.

Related Systems Engineering Factors

In spite of the utilization of the techniques just outlined, we have generally found that they in themselves do not eliminate all catastrophic single point failures. It is necessary to have separate design reviews and analyses of failure modes and their effects to assure the identification of all single point failures. These activities are undertaken by special reliability engineers who do not have the "invented-here" feeling of the design engineer.

Another factor related to systems engineering is the recognition that even the best designs may fall prey to discrepancies which occur in the manufacturing process. Routine aircraft quality control methods are inadequate to achieve manned space flight goals. For this reason, inspection efforts are materially increased both in-plant and at suppliers' facilities. Sampling techniques are completely eliminated except for items such as nuts and bolts and it is necessary to carefully record each step in a component's history and to establish a central record system to assure positive retention and rapid access to these records.

The practice of writing off failures as isolated cases cannot be tolerated and, by careful analysis and testing, the causes of most malfunctions which occur during ground or flight testing can be identified. Meticulous attention to this failure analysis and follow-up with corrective action is an essential feature of any safety program. It is highly undesirable to fly equipment with a questionable history.

Still another factor strongly related to systems engineering is the approach taken to subsystem and system testing. The Gemini development philosophy was based on the premise that confidence could be achieved through heavy emphasis on ground testing and that a very limited number of unmanned flights could serve to validate the approach. In the Apollo Program, the Gemini philosophy of limited unmanned flights is being continued, but adding to it the all-up space vehicle concept. This concept requires that, to the extent practicable, all flights will be scheduled as complete space vehicles. This approach intensifies reliance on a comprehensive ground test program which involves development, qualification and integrated systems tests. The ability to capitalize on success offers us the potential for early meaningful missions at a significant cost saving.

Emphasis in the ground test program is focused on design verification, qualification and acceptance testing of components and subsystems, and comprehensive factory and launch site checkout of total systems. The ground test program, however, not only involves rigorous qualification and checkout, but also includes many special test articles for integrated testing. They include those for propulsion tests, systems compatibility tests, facility checkout, dynamic and structural tests and many others. Twenty-one additional spacecraft test articles provide test data on dynamic loads and response, water landing, parachute recovery, flotation, structural integrity, thermal-vacuum characteristics and abort characteristics to insure operational reliability over the entire flight regime. A typical example of this type of an integrated test article is shown in Figure 12. The photograph shows an Apollo command and service module in a 60 x 120 foot Space Environmental Simulation Chamber. Complete Systems Functional Tests are performed in a manned operation while the spacecraft is exposed to liquid nitrogen cooled balls and a vacuum of 10^{-5} torr. A solar simulator radiates heat onto the spacecraft surfaces, programmed as would occur in an actual space flight. This test facility in combination with a flight-type test article permits the evaluation of the combined capability of man and spacecraft systems to perform to the requirements of present and future space flights.

An Apollo test program phasing chart is presented in Figure 13. A high level of ground test efforts commenced at the outset of the Apollo Program and will be sustained through the early manned flights. It is planned that all ground qualification tests be completed prior to initiation of the first manned Apollo flights.

Systems Engineering of Special Projects

Many special systems integration activities occur throughout the life of a program. Included in these efforts are such areas as extravehicular activities and scientific and technical experiments. The Gemini experiment program will be used to illustrate the factors involved.

The experiments integrated in the spacecraft ranged from relatively simple ones such as cameras to complex experiments which had to be structurally mounted, thermally controlled and automatically deployed for taking measurements. In addition, some experiments had extensive data recording and transmission requirements. Even the relatively simple experiments, however, presented a significant integration problem due to the small confines of the spacecraft cabin. Most of the remaining usable space was filled with experiment and crew equipment. Experiments were mounted or stowed on the overhead hatches, the cabin walls, and even on the floor, as shown in Figure 14. Experiments which could be mounted outside the cabin did not present a significant stowage problem; however, they tended to be more complex since they could not generally be manually operated and had to have automatic provisions. An example of an experiment with complex integration requirements is shown in Figure 15.

Portions of this experiment which measured ultraviolet and infrared radiation in space were mounted throughout the spacecraft. The sensors, one a liquid neon cooled spectrometer, involve pyrotechnically operated hatches, and special deployment and alignment provisions.

A significant portion of the crew training was devoted to the experiments. The training involved both learning the experiment objectives and equipment operation. The crew training turned out to be a two-way street since many modifications in the experiment design were suggested by the crews to improve the equipment's operational characteristics. It was important for the crew to understand the experiment objectives and underlying principles to take full advantage of their discretionary ability and modify the experiment plan as required to adapt to the situations.

Mission planning for the experiments was a very complex problem involving many iterations of the flight plan to fit the experiments into the proper place. Some experiments had to be performed on the night side of the orbit, others on the daylight side. Some experiments had to be performed early in the mission, others late in the mission. Some experiments were designed to measure the near earth radiation, others were damaged by it and provisions had to be made to minimize the effects of radiation. Some experiments worked best at high altitude, others at low altitude. In addition to considerations such as these, there were others such as payload margin and propellant consumption. Every effort was made to utilize the payload capability available in order to provide for the greatest possible experiment capability. Propellant tanks were added to the spacecraft to maximize the amount of propellant available for this part of the flight program.

There were a total of fifty-two experiments in the Gemini Program. In general, each experiment was flown several times to take advantage of varying flight conditions. This resulted in one hundred and eleven experiment missions, an average of eleven experiments per flight. The experiments were divided into three categories; scientific, technological, and medical. A wide variety of very interesting and useful results were obtained from these experiments and have been reported on in numerous technical and scientific papers. As an example, there are the ultraviolet spectrographic photographs obtained of the star Canopus during standup extravehicular activity (Figure 16). The lines in the upper end of the spectrum (lines of magnesium and iron) are not transmitted by the earth's atmosphere and were recorded for the first time in the spectrum of a star other than our sun.

In-Flight and Post-Flight Considerations

Although the main emphasis in systems engineering prior to flight is to achieve a high degree of assurance that a mission will proceed as planned, one must also consider the possibilities that events can occur which will change the mission. Therefore, a substantial amount of effort has been placed on considerations of alternate missions which will achieve maximum benefits from the flight in the face of certain contingencies. This aspect of planning involves such factors as re-cycle plans as a result of launch delays, alternate mission plans related to major failures during launch which abort a mission, and contingency flight plans because of problems evidenced during the orbital flight. Obviously, it is not possible to do planning for each detailed failure that might occur, but rather to consider basic classes of problems for which other approaches can be established. In the flight program to date, a substantial amount of effort has been placed on this aspect of our flight operations and, in the majority of the flights, this activity has paid off in some way. Generally, this planning evolves from a series of logic diagrams from which such things as re-cycle plans, alternate mission plans, contingency flight plans and the like are developed.

A highly simplified version of a logic diagram indicating alternate mission possibilities concerned with one Gemini flight is presented in Figure 17. Also included on the figure is an indication of how the mission was actually carried out in the face of certain contingencies. In the Gemini IX mission, the basic plan was to launch a target vehicle into orbit, followed by the launch of the spacecraft which would then rendezvous and dock with the target vehicle. Subsequent to docking an extravehicular program was to be conducted, followed by a series of re-rendezvous operations to investigate purely optical rendezvous techniques as well as more difficult approach geometries. The mission then ended with the reentry and landing of the spacecraft. The attempt to launch the target vehicle was a failure because of a control system problem in the launch vehicle. A plan had been previously developed to immediately place a backup launch vehicle on the launch pad and to utilize a simpler target vehicle, also maintained in readiness. The details of this re-cycle plan showed that the checkout process of the replacement system could be accomplished in two weeks, providing the determination of the cause of failure and the resulting corrective action could be concluded within that time period.

The re-cycle plan was initiated immediately after the failure and in parallel with the failure analysis. It was possible to isolate the most probable cause of failure and secondary possibilities and to make appropriate modifications to the backup launch vehicle within the time frame planned. Thus, the new target was launched into orbit within the time period specified and was followed into orbit by the spacecraft. It may be noted at this point that contingency flight plans had been detailed for a number of basic in-flight contingencies such as not being able to achieve rendezvous or the inability to dock. On this particular flight the rendezvous was achieved without incident, but because a protective shroud on the target did not deploy properly during launch, the docking mechanism was not exposed and it was impossible to dock. At that point, a contingency flight plan was initiated as had been previously developed. Thus, in the actual mission, it was necessary to perform the re-rendezvous exercises prior to the extravehicular activity because undocked station keeping of the target would have resulted in prohibitive propellant consumption and forced elimination, not only of extravehicular activities, but many of the programmed experiments as well. In this manner, the flight operation was able to proceed smoothly into the new plan and achieve a majority of the mission objectives desired for this flight.

Even when missions proceed essentially as planned or proceed on a contingency basis, system or operational difficulties that occur must be corrected prior to initiation of the next flight. In the Gemini Program, an attempt was made to establish an analysis, reporting, and corrective action system which avoided this potential delay in the progress of the program and it was very successful.

In targeting for two-month launch intervals the publication of the mission evaluation report was set at thirty days. In turn, a major part of the data handling, reduction, and analysis activities took place in a period of approximately two weeks following each mission. This time scale presented a rather formidable task when one considers the volume of data accumulated during the mission. The Gemini flight data production rate can be envisioned from the information presented in Figure 18. The figure also indicates the number of tabulations and plots required for the analysis of a typical long duration mission. The acquisition of large quantities of data, combined with the need to evaluate and quickly resolve anomalies, resulted in the utilization of a methodology for selective reduction of data which has proved effective. This selection process involves real time mission monitoring by evaluation engineers which, in turn, results in a judicious selection of flight segments for which data are needed. This monitoring, combined with the application of compression methods for the presentation of data, has made it possible to complete evaluations on a timely basis.

All problems were not necessarily solved at the end of the thirty-day reporting period, but problem isolation, impact evaluation, and corrective action initiation were possible in this time period. In carrying out these activities, a formal task group is set up with personnel assigned who have been actively working in specific areas before the flight and during the flight. This approach provides personnel already knowledgeable with the background of the particular flight. Corrective action is initiated as soon as the problem is isolated and defined.

Summary

As implied from the discussions in this paper, systems engineering encompasses all phases of a manned space flight program. An attempt has been made to describe some of the major concepts utilized in the United States to provide for a logical development of the flight hardware, for the successful conduct of flight operations, and for achievement of maximum benefits from each mission. We are naturally in the process of continuing these concepts in the on-going Apollo Program in order to meet its lunar landing objective.

The greatest underlying influence to our approach is the assurance of flight safety, but within that constraint, a strong secondary influence is the achievement of mission success. Undoubtedly, in the future, new and more extended mission objectives will be defined and some alteration to the present concepts can be expected because of the peculiarities of these missions. However, the major factors of the present approach appear sound and worthy of continued consideration.

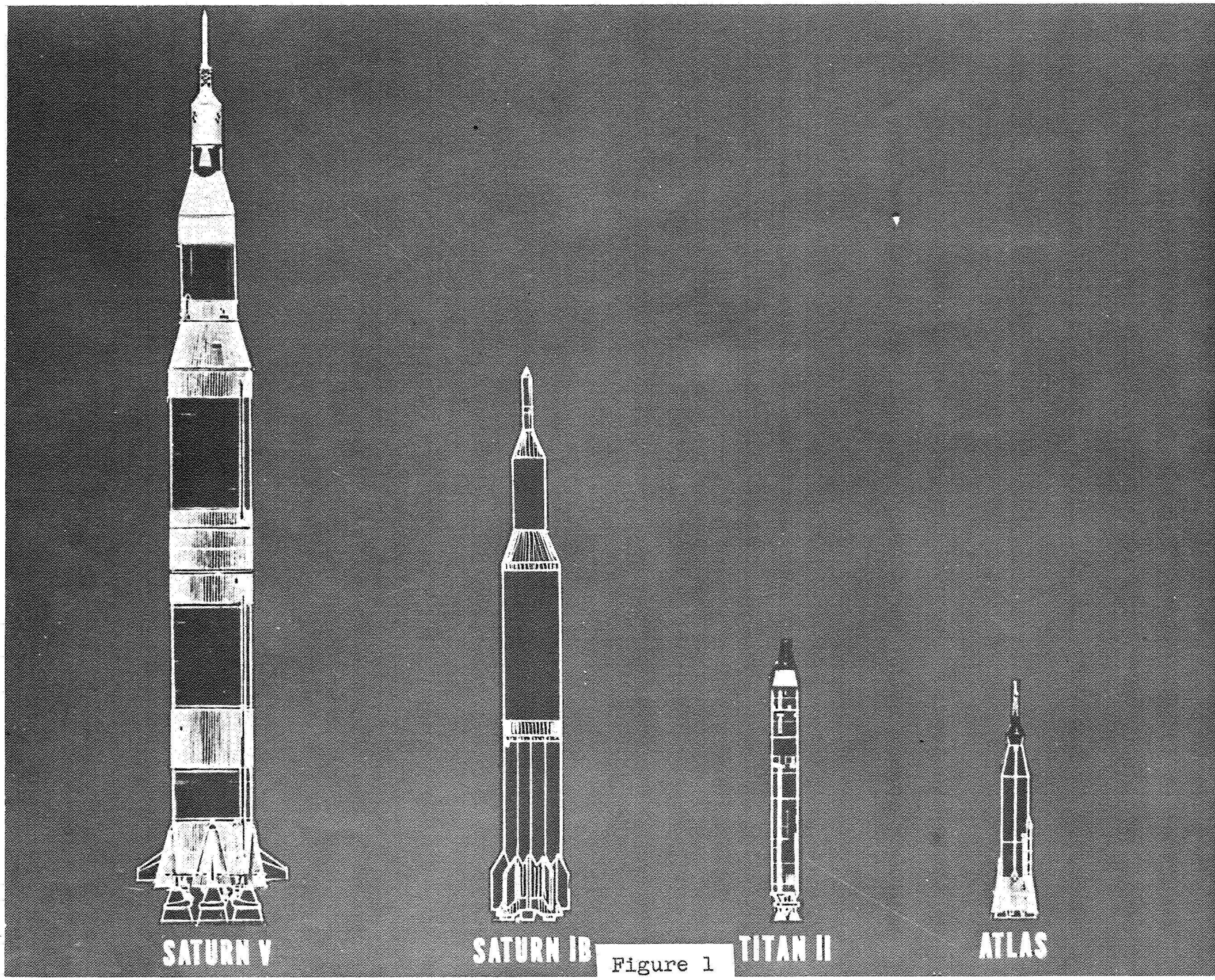

Figure 1

PRIMARY PROGRAM OBJECTIVES

MERCURY:	MANNED ORBITAL FLIGHT AND SAFE RETURN
GEMINI:	LONG DURATION FLIGHT AND RENDEZVOUS
APOLLO:	MANNED LUNAR LANDING AND SAFE RETURN

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Figure 2

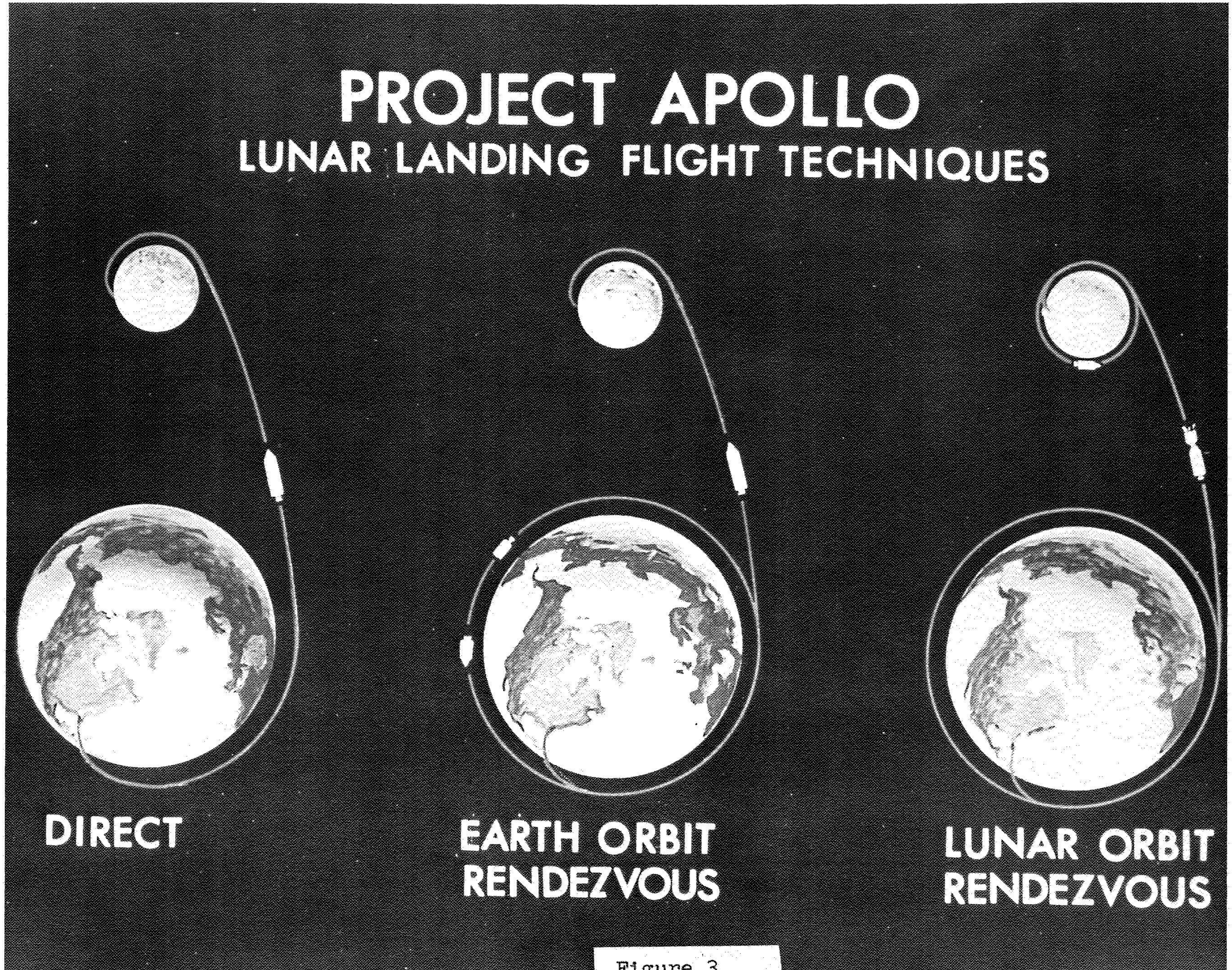
PROJECT APOLLO
LUNAR LANDING FLIGHT TECHNIQUES
DIRECT
EARTH ORBIT RENDEZVOUS
LUNAR ORBIT RENDEZVOUS

Figure 3

MODE COMPARISON

	LUNAR ORBIT RENDEZVOUS	DIRECT	EARTH ORBIT RENDEZVOUS
SAFETY	PROBABLY BETTER	APPROXIMATELY ALIKE	APPROXIMATELY ALIKE
MISSION SUCCESS PROBABLITY	BEST		
COST ESTIMATES	LOWEST		
DEVELOPMENT REQUIRED	LEAST		
ORDER OF FINAL CHOICE	FIRST	SECOND	THIRD

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Figure 4

MISSION PLATEAUS

1. PRELAUNCH
2. EARTH PARKING ORBIT
3. TRANSLUNAR COAST
4. LUNAR ORBIT PRIOR TO LM DESCENT
5. LM DESCENT
6. LUNAR SURFACE STAY
7. LM ASCENT
8. LUNAR ORBIT SUBSEQUENT TO RENDEZVOUS
9. TRANSEARTH COAST

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Figure 5

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ENERGY REQUIREMENTS FOR LUNAR LANDING MISSION

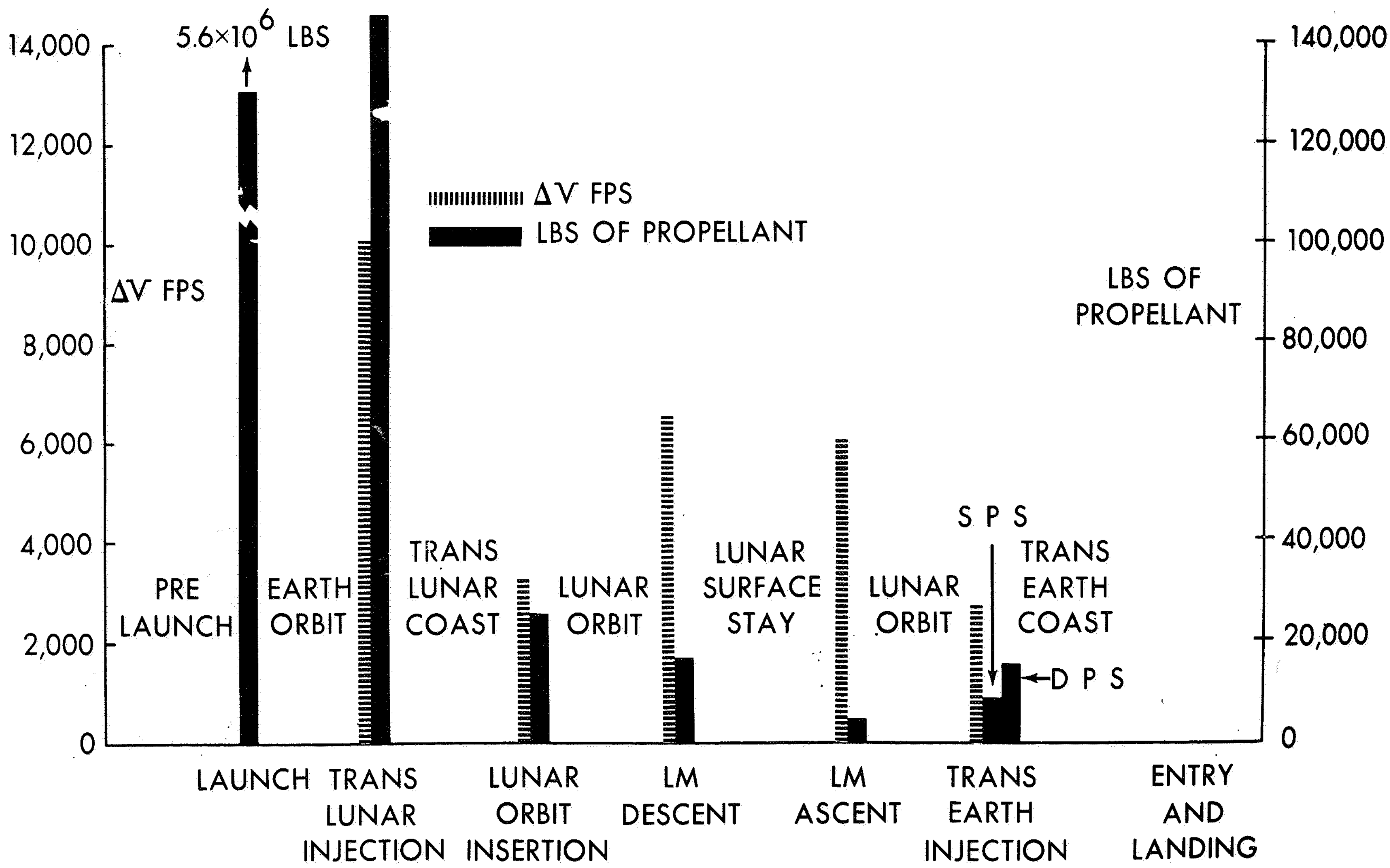

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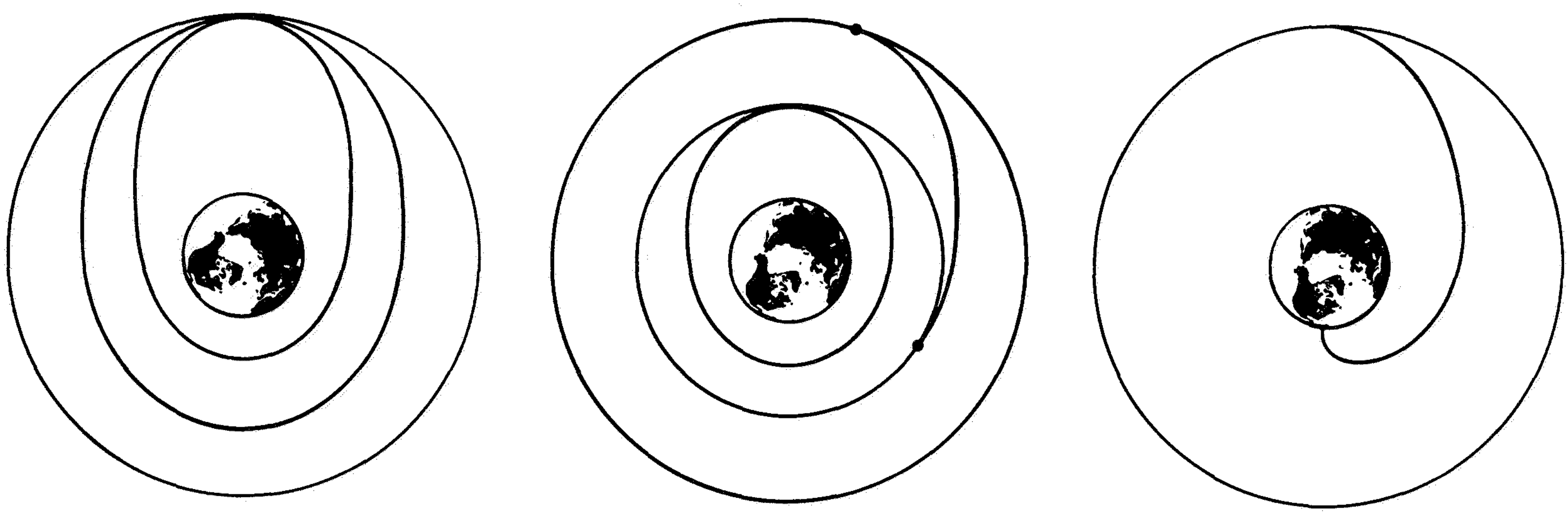
Figure 6

RENDEZVOUS MISSION PLAN DEVELOPMENT



TANGENTIAL PLAN   COELLIPTICAL PLAN   FIRST APOGEE PLAN

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Figure 7

GEMINI GUIDANCE AND CONTROL SYSTEM

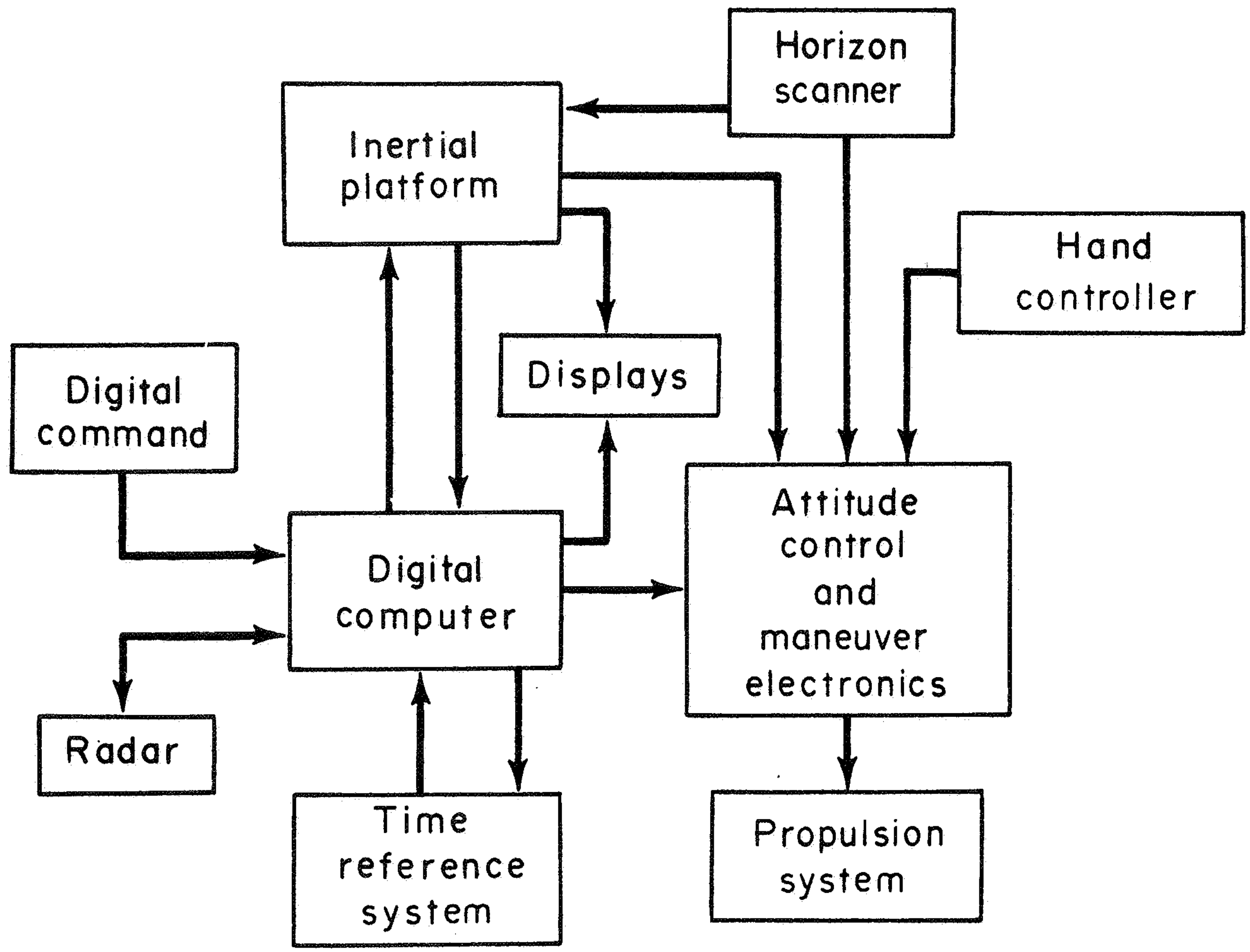
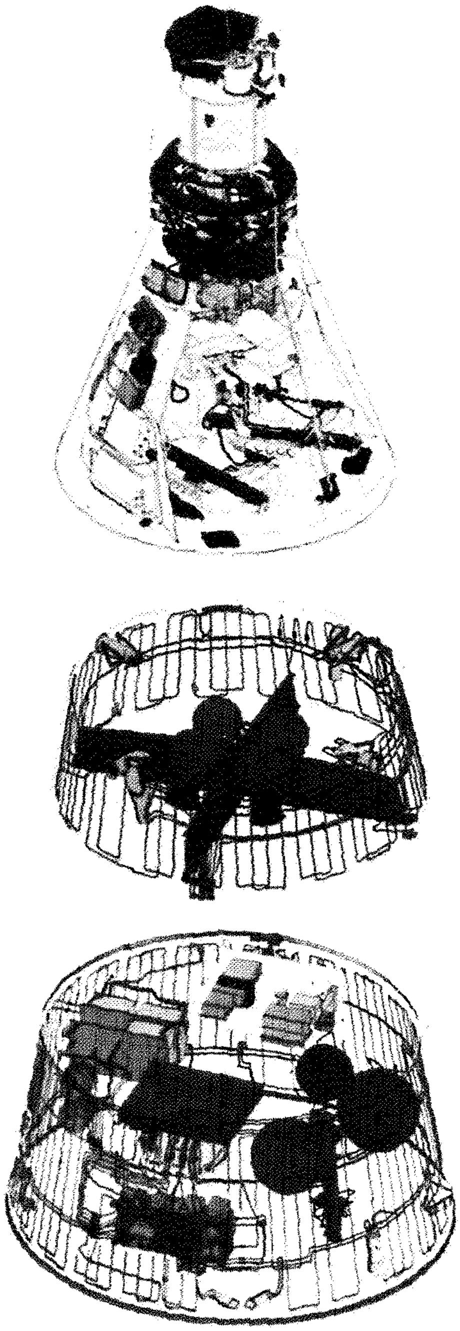


Figure 8

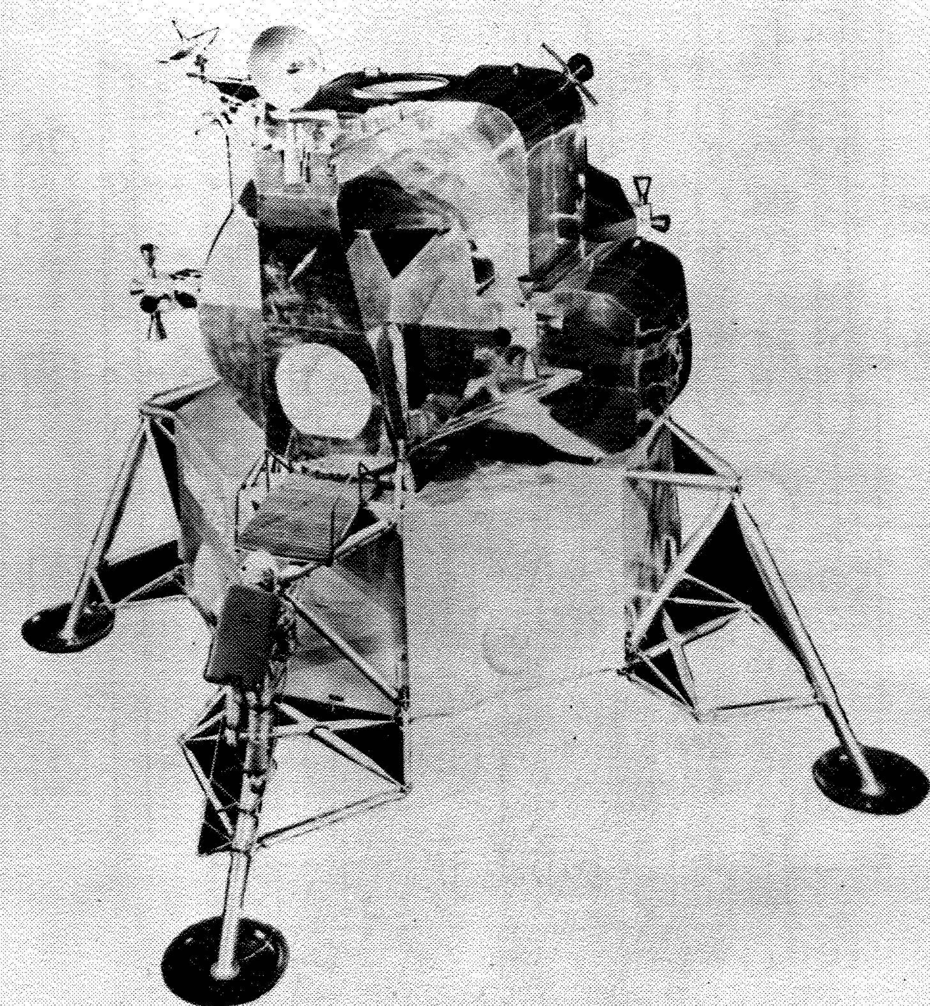


OPERATIONAL DESIGN CONFIGURATION

- MODULAR CONSTRUCTION
- INDEPENDENT SYSTEMS
- SEPARATE TEST POINTS
- INDIVIDUAL ACCESSIBILITY
- RELIABLE PROCESSES

Figure 9

LUNAR MODULE CONFIGURATION



NASA MC66-5057

Figure 10

NASA S 64 5994

GEMINI ELECTRICAL POWER SYSTEM

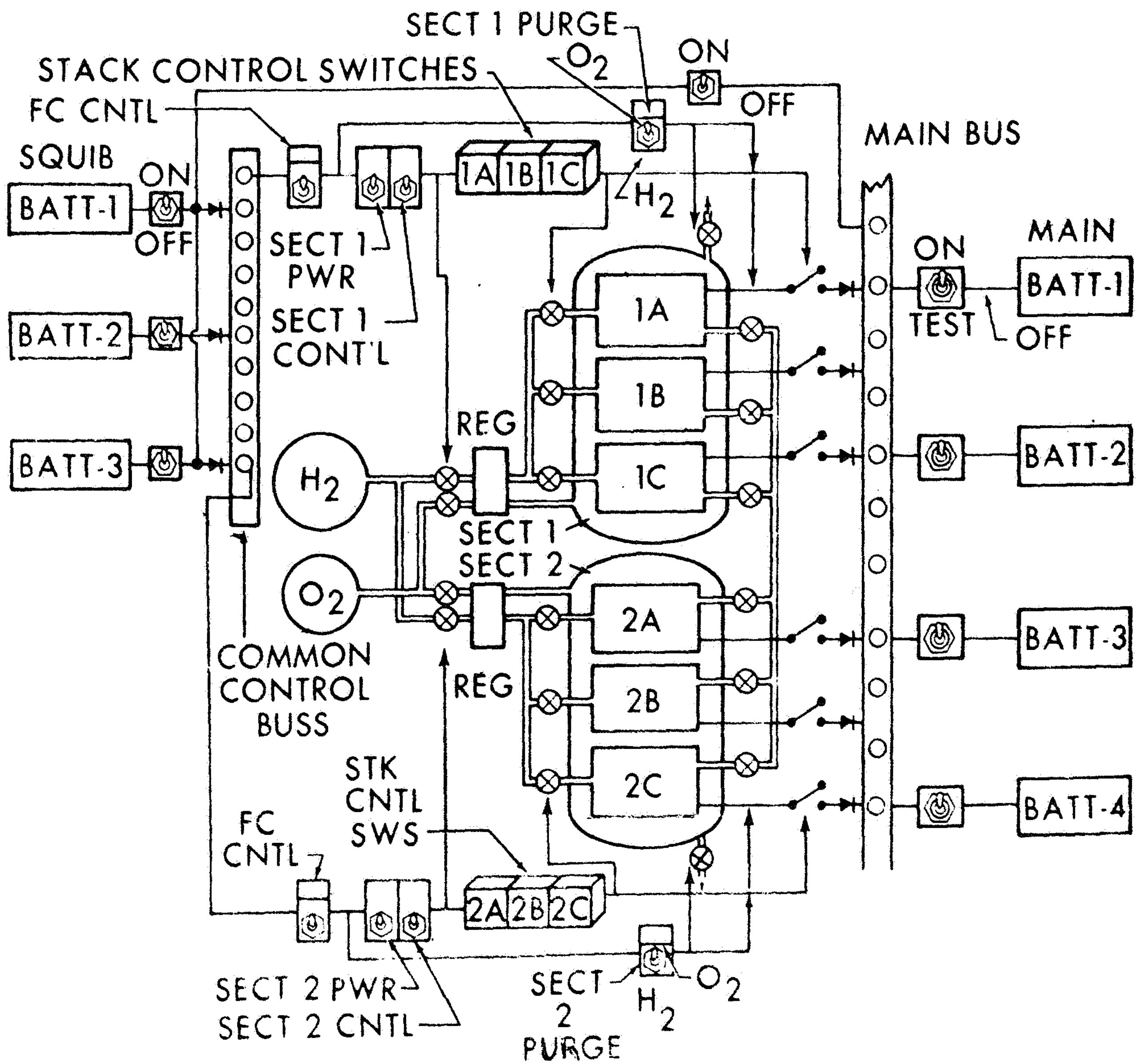


Figure 11

MANNED CSM
GROUND TESTING

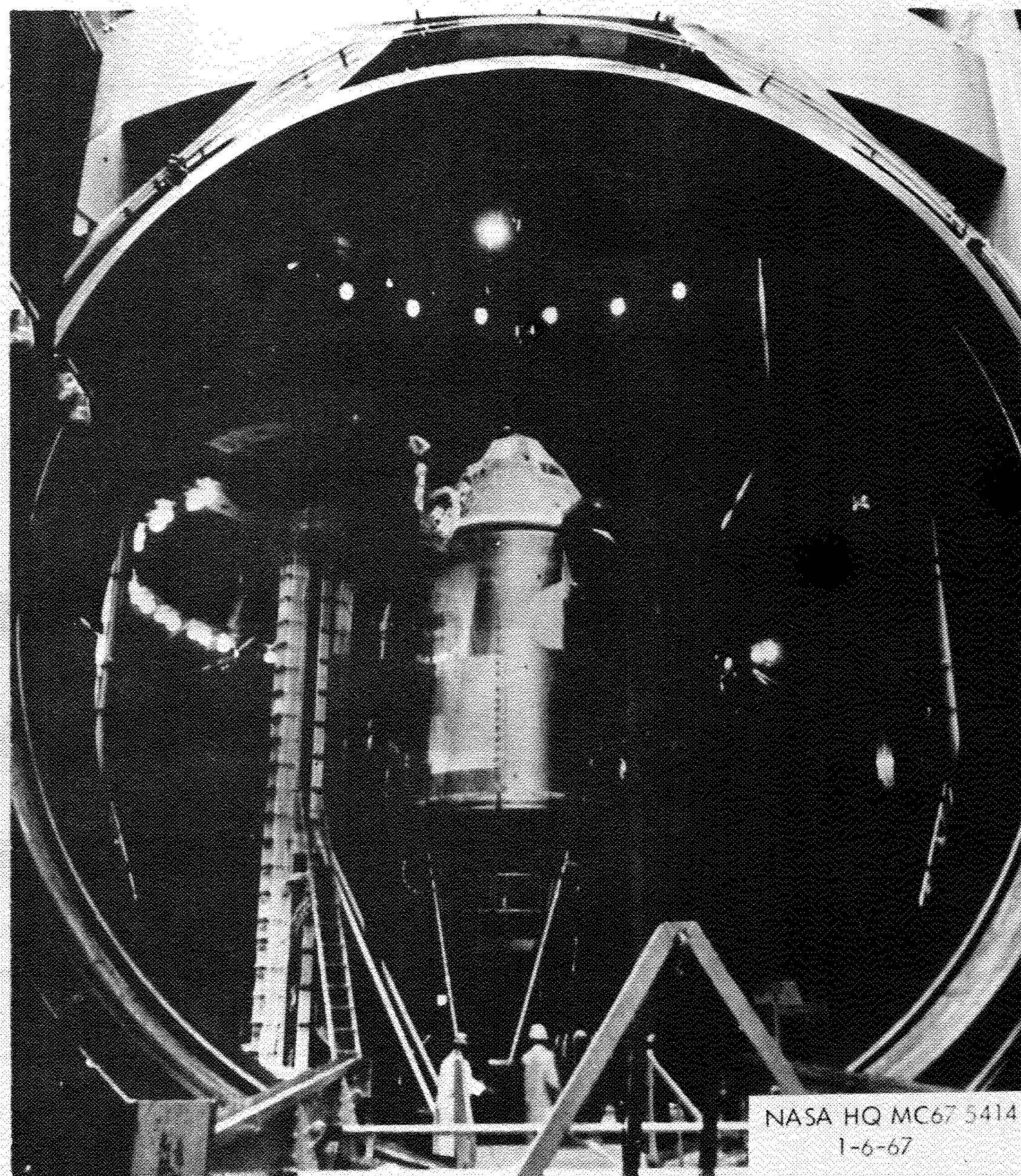


Figure 12

APOLLO TEST PROGRAM PHASING

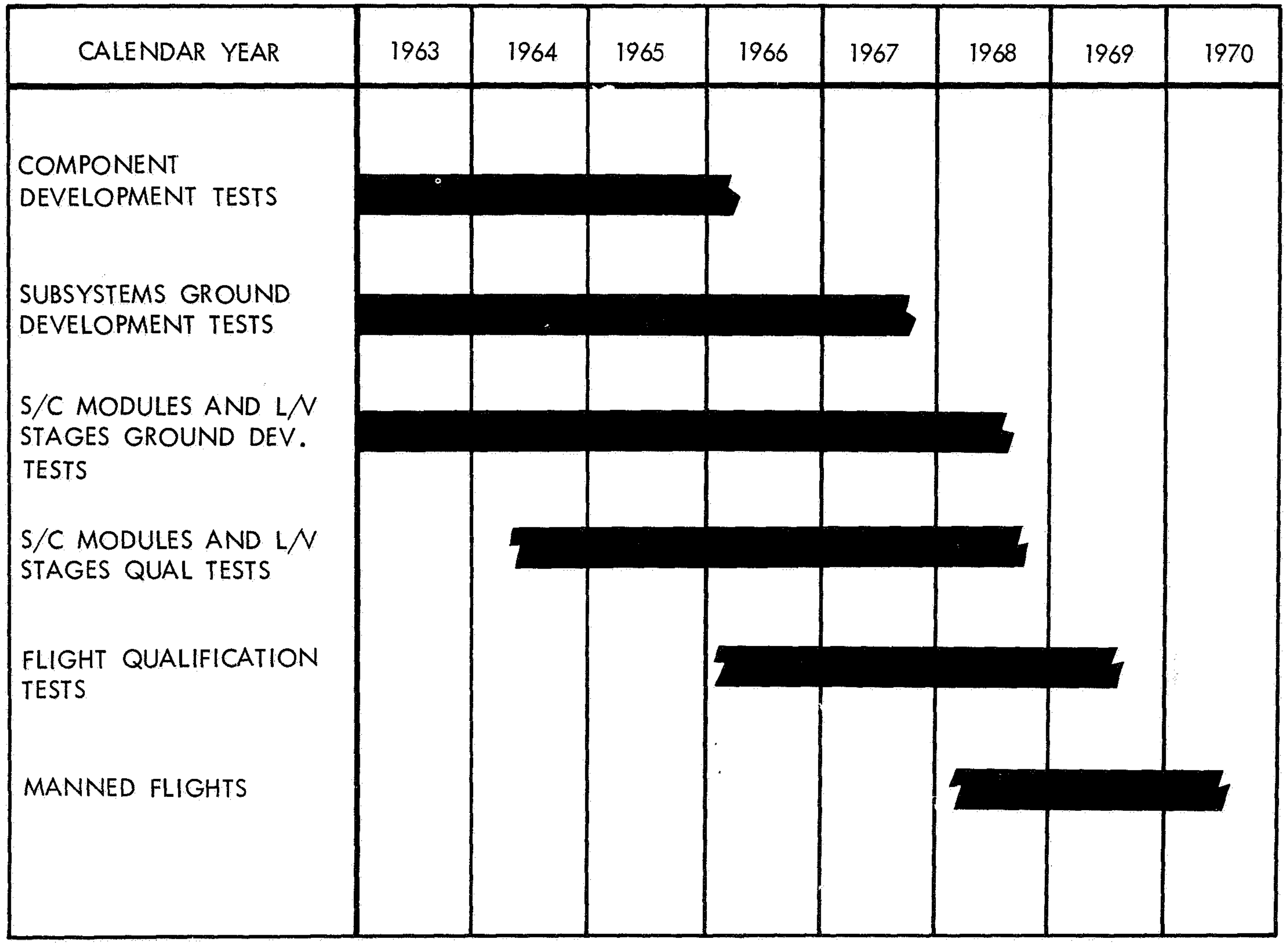


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Figure 13

GEMINI EXPERIMENT STOWAGE

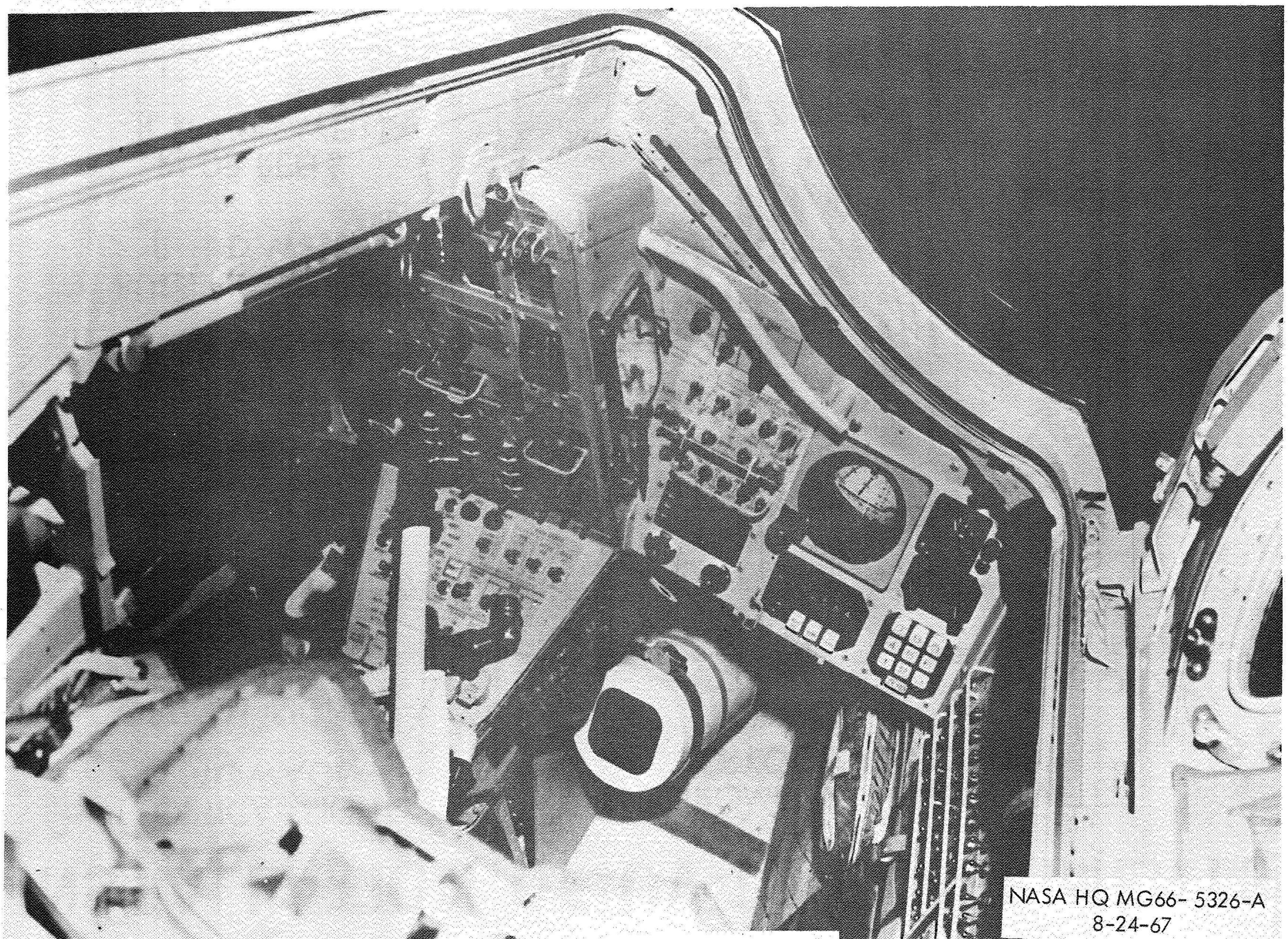


Figure 14

INSTALLATION OF UV-IR EXPERIMENTS

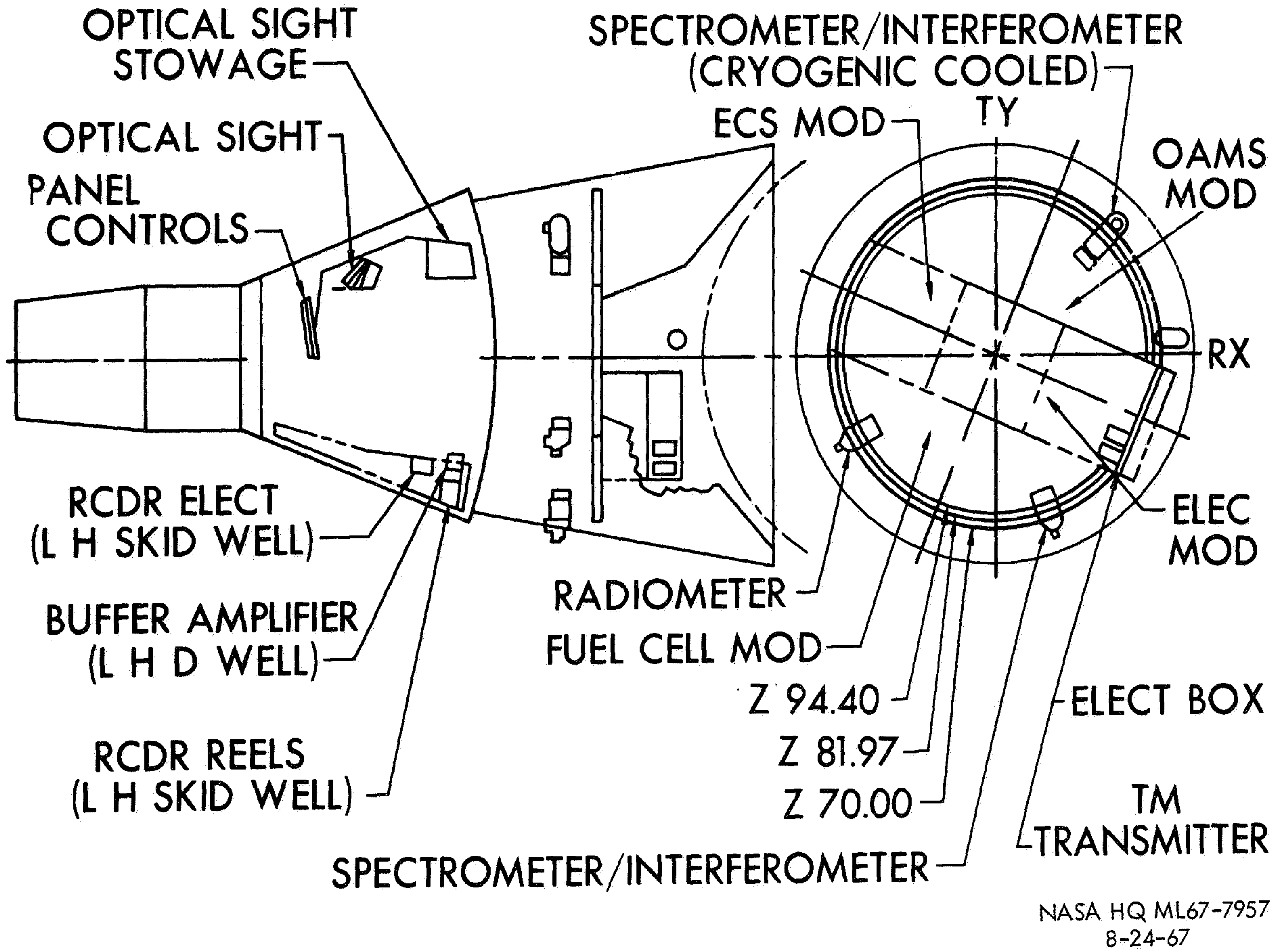
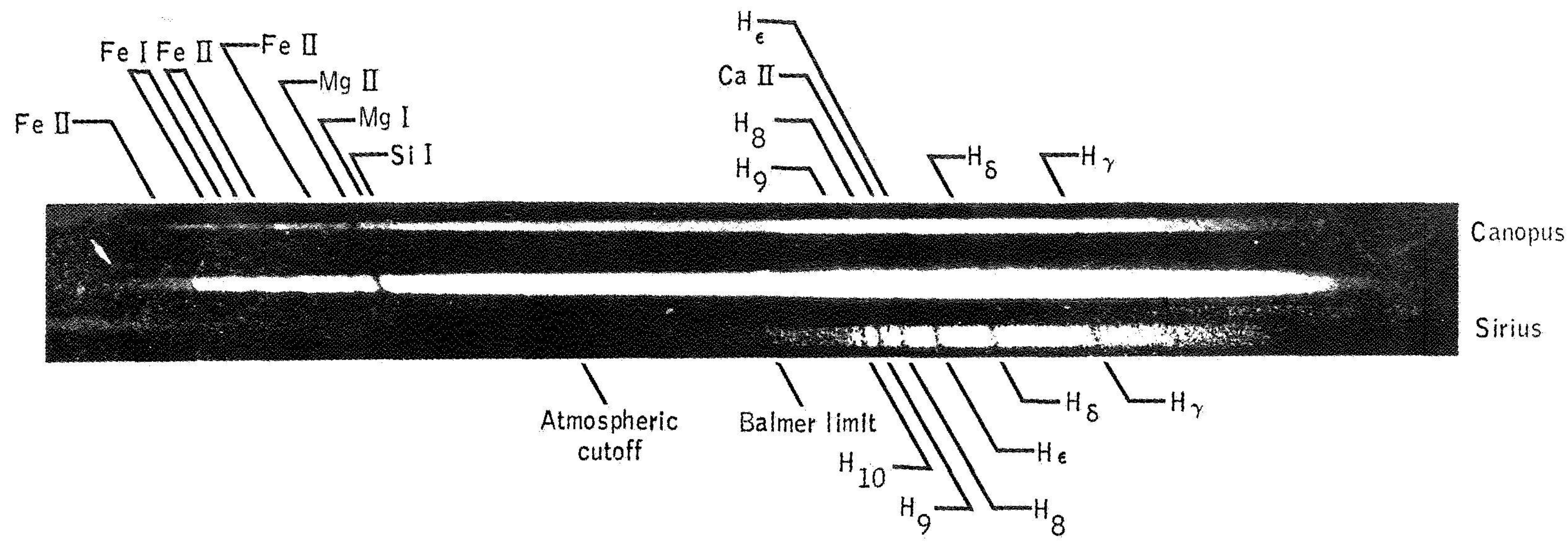


Figure 15

COMPARATIVE SPECTRA OF CANOPUS AND SIRIUS

Canopus photographed from Gemini XI spacecraft



Sirius photographed from Earth's surface

The opaqueness of the earth's atmosphere is clearly shown by the lack of spectral data in the ultraviolet band from Sirius.

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Figure 16

GEMINI IX-A MISSION

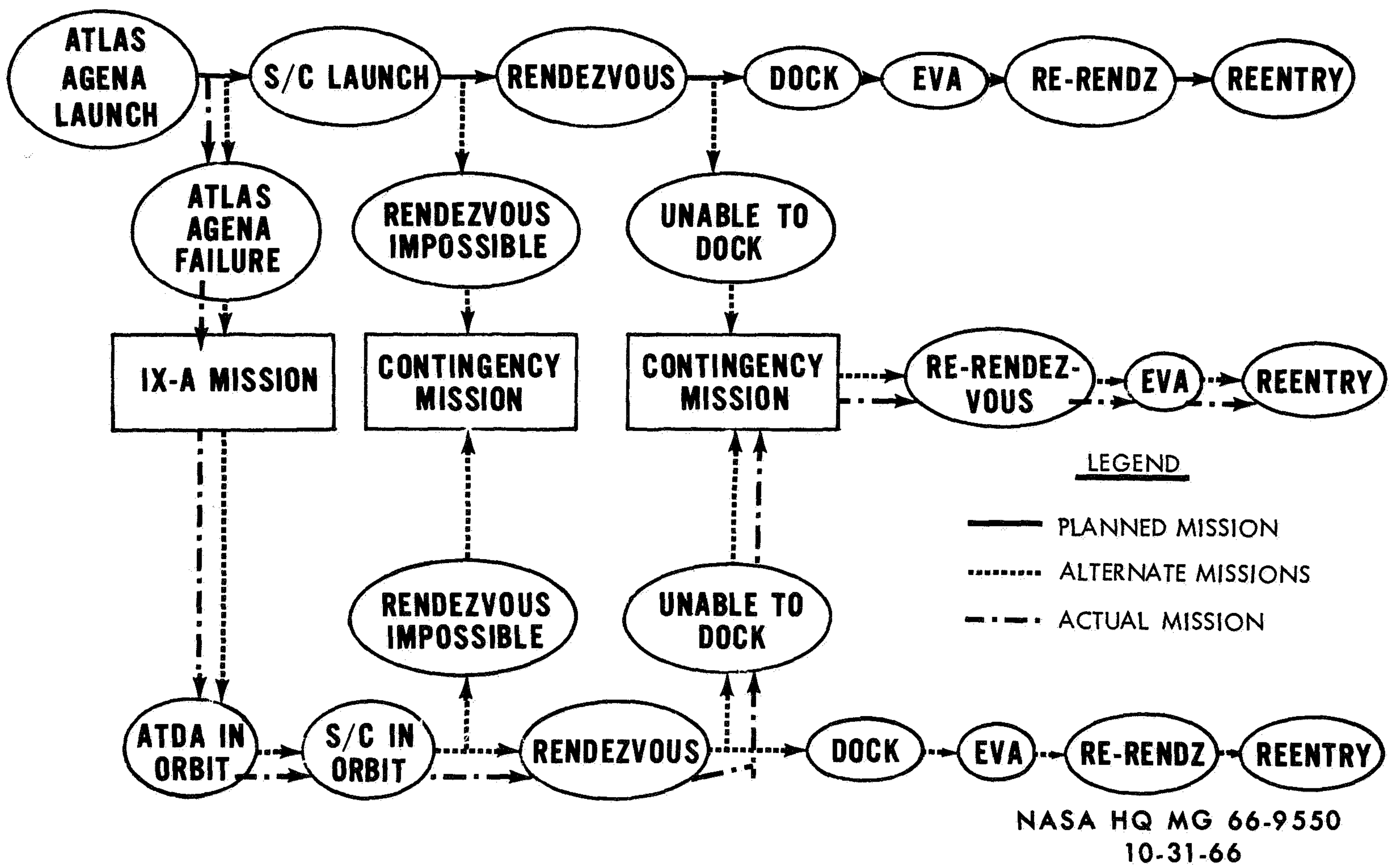

Figure 17

GEMINI FLIGHT DATA PRODUCTION RATE

EACH SECOND:

REAL TIME	51200 BITS
DELAYED TIME	5120 BITS

EACH REVOLUTION:

DELAYED TIME ANALOG	2000 000 DATA POINTS
DELAYED TIME EVENTS	4000 000 INTERROGATIONS

GEMINI V (8-DAY MISSION):

DELAYED TIME ANALOG	250 000 000 DATA POINTS
TABULATIONS REQUIRED	1 000 000 PAGES
PLOTS REQUIRED	750 000 PAGES

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Figure 18

GPO 929-340